

Optimized sowing time windows mitigate climate risks for oats production under cool semi-arid growing conditions

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ARTICLE INFO

Keywords:

APSIM-Oats
Water limited potential yield
Climate change
Cumulative probability
Optimal sowing time window
Yield gap

ABSTRACT

Year to year variability in weather poses serious risks to crop production in the environmentally fragile agroecosystems of cool semi-arid areas, and future climate changes might further aggravate those risks. This study aims to quantify the contribution of altered sowing time windows to reduce climate risk for the production of oats (*Avena sativa*), a crop that is well adapted to short growing seasons and low rainfall. The APSIM-Oats model was calibrated and validated for phenology, above-ground dry matter and yield using data from field experiments with five sowing dates, conducted from 2009 to 2013 in Inner Mongolia, China. The model was used to determine yield trends and yield-limiting factors under rain-fed conditions using historical weather data. Changes in temperature had greater impact on crop production than changes in rainfall and the simulations indicated the importance of changed sowing windows to lengthen the growth duration and optimize water use. Delayed sowing of oats, 10 days later than current practice, ensured more secure temperature and rainfall conditions from emergence to flowering and substantially increased yields and decreased climate risk. Delayed sowing also reduced climate risk under two future climate scenarios, RCP4.5 (stabilize growth) and RCP8.5 (high greenhouse gas emission). We conclude that adaptation of sowing time of oats provides a practical strategy for enhancing yield and mitigating climate risk under climate change.

1. Introduction

Inner Mongolia, China, is an environmentally fragile region that is prone to erosion of agricultural soils due to low rainfall, a short growing season, and strong winds during winter when the soil is bare. Inner Mongolia is nevertheless an important area for crop production and livestock farming (Li et al., 2015). Current trends towards higher temperature and changed patterns of rainfall could affect the sustainability of the current agricultural practices in Inner Mongolia, and require adaptations in land use practices (Smit and Skinner, 2002). Even without climate change, the large seasonal and inter-annual climate variability and vulnerable soils severely affect the local rain-fed agriculture.

Oats is a well-adapted food and forage crop for the Inner Mongolian climate due to its short growth duration and drought resistance (Dar

et al., 2014). Inner Mongolia is the most important production area of oats in China, and accounts for 30% of the national production (National Bureau of Statistics of China, 2010). Yields are, however, low, varying from 524 to 960 kg ha⁻¹ in the past 60 years, because the growing season is short and rainfall limited. As rainfall is highly variable from year to year, farmers apply little fertilizer, which is a third reason for low yields. Decreasing trends in rainfall over the last 60 years, and high seasonal variability, result in large climate risks and require adaptation strategies (Li et al., 2015). To be able to formulate effective adaptation strategies, it is crucial to identify the response of oats growth and yields to the limiting meteorological factors.

Amongst the many mitigation measures that may be taken, shifting sowing dates is one of the easiest and most effective ways to align the needs of a crop with seasonal patterns of rainfall and temperature. Early sowing reduces risks of late frost damage in winter wheat in north-

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<https://doi.org/10.1016/j.agrformet.2018.12.019>

Received 7 August 2018; Received in revised form 15 October 2018; Accepted 28 December 2018

Available online 03 January 2019

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eastern Australia, doubling gross margins (Howden et al., 2003). Simulation studies indicate that future warming in Australia allows early planting which could increase wheat yield by up to 36%, assuming 750 ppm CO₂, 4 °C warming and no change in rainfall compared to current climate (Crimp et al., 2008). In Inner Mongolia, low and variable rainfall and low temperatures in spring and autumn limit agricultural production. The attainable water limited oats yield in this region under present and future climates have not been studied. Furthermore, it is unknown whether and to what extent changes in sowing time could reduce risks of drought and cold stress.

Assessing climatic risk on crop production can be improved by using dynamic crop simulation models, provided long-term climatic data are available. The Agricultural Production Systems Simulator (APSIM) is an effective and powerful tool to evaluate the potential response of crop productivity to climate change and assess climate risks and adaptation options (Holzworth et al., 2014). However, the oats model in APSIM is not well validated in China.

The objectives of this study were therefore to: (1) calibrate and validate the APSIM-oats model under rain-fed conditions in a cool and dry environment; (2) identify the critical meteorological factors limiting oats growth and yield; and (3) explore whether changed sowing time can enhance oats yield and reduce climate risk under present and future climates.

2. Materials and method

2.1. Study area

Experimental studies were conducted in Wuchuan county (111.41 °E, 40.49 °N), Inner Mongolia. The local climate is cool and semi-arid with a mean annual precipitation of 348 mm and a standard deviation between years of 80 mm, and a mean frost-free period of 153 days and a standard deviation between years of 15 days (1961 to 2015). There are on average 2700 sunshine hours per year. The historical annual mean air temperature is 3.6 °C with a standard deviation of 1.0 °C from 1961 to 2015. Winters are cold and dry, and summers are warm. The climate allows one harvest per year. The region is characterized as an agricultural and pastoral ecotone for which oats is one of most suitable crops.

2.2. Site description and field experiments

Two field experiments were conducted on oats at the Scientific and Observational Experimental Station of Agro-environment in Wuchuan, a typical research station built by Ministry of Agriculture for representative agriculture and pasture ecotone, from 2009 to 2013. The soil bulk density of 0–100 cm soil layer is 1.45 g cm⁻³. The soil total N, available P, available K and organic matter contents in 0–100 cm layer are 1.09 g kg⁻¹, 4.96 mg kg⁻¹, 105.27 mg kg⁻¹, and 13.4 g kg⁻¹, respectively.

Experiment 1 ran over five consecutive years in 2009–2013 with five sowing dates each year. The cultivar was Caoyou 1, and the sowing dates were: 8 May, 13 May, 18 May, 23 May and 28 May in 2009, 26 April, 6 May, 16 May, 26 May and 5 June in 2010 and 2011, and 26 April, 6 May, 16 May, 26 May and 31 May in 2012 and 2013. Row spacing was 25 cm and plant density was 128 plants m⁻² (sowing rate 11.3 g m⁻²). The row orientation was east to west. Each year, a basal fertilizer was given with 37.5 kg ha⁻¹ urea (46.3% N), 70 kg ha⁻¹ (NH₄)₂HPO₄ (18% N, 46% P₂O₅) and 37.5 kg ha⁻¹ KCl (60% K₂O). Treatments were arranged in a randomized complete block design with four replicates. Plot area was 25 m² (5 m in length × 5 m in width). Results of experiment 1 were used to calibrate and validate APSIM for oats phenology, biomass growth, and yield.

Experiment 2 was conducted at the same site in the same five years, using the same variety ‘Caoyou 1’, but with a higher plant density than in Experiment 1 and only one sowing date in each year (20 May, the

conventional date). Row spacing was 20 cm, resulting in a plant density of 160 plants m⁻² (sowing rate 14.0 g m⁻²). Row orientation was also east to west. A basal fertilizer each year was given with 150 kg ha⁻¹ urea, 90 kg ha⁻¹ (NH₄)₂HPO₄ and 60 kg ha⁻¹ KCl. Treatments were arranged in a randomized complete block design with four replicates. Plot area was 60 m² (10 m in length × 6 m in width). Results of this experiment were used for model validation.

No irrigation was applied in either experiment. Weeds were removed manually. Other management was carried out according to local farmers’ practices.

2.3. Measurements

Phenological development, above-ground dry matter and yield were measured in each plot in each year in both experiments. Growth dynamics during the season were measured using periodic harvests.

Observations on phenology were made on ten plants per plot at 2-day intervals, to determine the times at which 50% of the plants reached the stages of emergence, flowering and maturity.

Above-ground dry matter was measured at 15 days intervals during the crop growing season. A sub-sampling area of 1 by 1 m was selected in each plot on each sampling occasion. The sub-sampling area was at least 1 m away from previous harvesting to avoid edge effects caused by sampling.

To determine final yield, oats was harvested from a sampling area of 4 m² (2 m in width × 2 m in length) in each plot for both experiments. The grain was sun dried to approximately 14% water content. Dry matter was measured for a random subsample of 10 plants from the sampling area. These plants were separated into stems, leaves and reproductive organs. After measuring fresh matter, the samples were dried in an oven at 80 °C for 2 days until they reached a constant weight.

2.4. Climate and soil data

2.4.1. Climate data

Climatic data including daily maximum and minimum air temperatures, sunshine hour, and precipitation from 1961 to 2015 were obtained from a standard weather station of the local meteorological bureau at the study site. Daily solar radiation was calculated from sunshine hours using the Angstrom formula with parameters 0.5 for *a* and 0.25 for *b* (Black et al., 1954; Jones, 1992).

For future scenario analysis, climate projections for 2016 to 2070 were taken from the output of Representative Concentration Pathways (RCPs) with a spatial resolution of 50 km × 50 km produced by 5th Phase of Coupling of Model Intercomparison Program (CMIP5) (Taylor et al., 2012). RCP4.5 is a scenario that assumes the use of technologies that result in a stabilized economic growth rate and intermediate greenhouse gas emissions and a radiative forcing that stabilizes at 4.5 W m⁻² in the year 2100 (Thomson et al., 2011; Taylor et al., 2012). RCP8.5 assumes continued high energy demand and increasing greenhouse gas emissions, and the radiative forcing increases throughout the twenty-first century, reaching a level of 8.5 W m⁻² at the end of the century (Riahi et al., 2011; Taylor et al., 2012).

2.4.2. Soil data

The soil data used in this study included the soil bulk density (BD), saturated volumetric water content (SAT), drained upper limit (DUL) (field capacity), and 15 bar lower limit (LL15) (wilting point) in different soil layers (Table 1). Data were obtained from field observations following the procedure of He et al. (2009) and were used as input parameters in the model.

2.5. Description of APSIM-Oats model

APSIM version 7.6 was used in this study. A prototype oats model

Table 1
Calibrated parameters of APSIM-Oats for Inner Mongolia in 2009 and 2013.

Variable	Description	Unit	Value
tt_end_of_juvenile	Thermal time required from end of juvenile stage to floral initiation	°C d	425
tt_floral_initiation	Thermal time required from floral initiation stage to flowering	°C d	420
tt_flowering	Thermal time required in flowering to start of grain filling	°C d	150
tt_start_grain_fill	Thermal time required from start to end of grain filling stage	°C d	650
tt_end_grain_fill	Thermal time required from end grain filling to maturity	°C d	30
vern_sens	Vernalization sensitivity	—	0.5
photop_sens	Photoperiod sensitivity	—	2.0
potential_grain_filling_rate	Grain filling rate during grain filling	mg grain ⁻¹ day ⁻¹	0.0015
potential_grain_growth_rate	Grain growth rate from flowering to grain filling	mg grain ⁻¹ day ⁻¹	0.001
grains_per_gram_stem	Grains per unit weight of stem at anthesis	kernels g ⁻¹	25
max_grain_size	Maximum size of single grain	g grain ⁻¹	0.041
Node phyllochron	Potential node appearance rate	°C d node ⁻¹	135
Leaf size ^a	Potential leaf area per node	mm ²	node = 1, 1400 node = 5, 3700 node = 8, 4800 node = 10, 5600
Leaf number ^a	Number of leaves per node	Leaves node ⁻¹	node = 0, 1 node = 2, 2 node = 7, 14
Maximum HI	Maximum harvest index	—	0.50
RUE	Radiation use efficiency	g MJ ⁻¹	1.50
TPLA	Initial total leaf area per plant	mm ² plant ⁻¹	80
BD (0–100 cm)	Soil bulk density	g cm ⁻³	1.450
LL15 (0–40 cm)	Soil volumetric water content at 15 Bar lower limit	mm ³ mm ⁻³	0.090
LL15 (40–70 cm)	Soil volumetric water content at 15 Bar lower limit	mm ³ mm ⁻³	0.100
LL15 (70–100 cm)	Soil volumetric water content at 15 Bar lower limit	mm ³ mm ⁻³	0.120
DUL (0–100 cm)	Soil volumetric water content at drained upper limit	mm ³ mm ⁻³	0.320
LL (0–100 cm)	Lower limit (for plant available soil water)	mm ³ mm ⁻³	0.176
SAT (0–100 cm)	Saturated volumetric water content	mm ³ mm ⁻³	0.450

^a Parameter is interpolated linearly between different values according to node numbers.

was developed based on the wheat model within the APSIM simulation framework and it was subsequently applied to simulate the effect of starting soil water content on oat and hay production in the Mid-North region of South Australia (Peake et al., 2008). APSIM simulates oats development, biomass growth, and grain yield in response to temperature, photoperiod, radiation, soil water, and nitrogen conditions with a daily time-step. In the model (like in reality), the crop is harvested at the first late season frosts, whether the crop is mature or not (Zheng et al., 2014; Barlow et al., 2015). The model is driven by weather data, i.e. temperature, rainfall, radiation, and CO₂ concentration. The atmosphere CO₂ concentrations input in the model are actual (historical period) or projected values (future scenarios). Therefore, the CO₂ effects on crop growth and yield are included in the simulations.

Phenological development from sowing to maturity is separated into 8 phases marked with key phenological stages, i.e., sowing, germination, emergence, end of juvenile stage, floral initiation, flowering, start of grain filling, end of grain filling, and maturity. Each phase finishes after a cumulative thermal time is reached (thermal time target). Daily thermal time (TT, °Cd) is calculated using a triangular response model with three cardinal temperatures, T_b for base temperature, T_o for optimal temperature and T_m for maximum temperature.

$$TT = \begin{cases} T - T_b & T_b < T \leq T_o \\ (T_m - T)T_o/(T_m - T_o) & T_o < T \leq T_m \\ 0 & T \leq T_b \text{ or } > T_m \end{cases} \quad (1)$$

where T is actual air temperature. T_b , T_o and T_m are set to 0, 26 and 34 °C, respectively, based on initial calibration using data of field experiment 1.

Before flower initiation, the daily increment in accumulated thermal time is modified by multiplying TT (Eq. 1) with cultivar-specific factors f_v and f_D (0–1) accounting for sensitivity to vernalization (vern_sens) and photoperiod (photop_sens), respectively, similar to the CERES-

Wheat model (Sadras and Monzon, 2006). After flower initiation, f_v and f_D are set to 1.

Potential leaf area growth is simulated with leaf number per node, potential leaf size, and node appearance rate (node phyllochron, i.e., thermal time needed for node appearance, °C d node⁻¹). Actual leaf area growth is the potential rate reduced by carbon limitation and by water and nitrogen stresses for expansion growth. Daily biomass growth is calculated using radiation interception and radiation use efficiency (RUE, g MJ⁻¹), reduced by nitrogen and water stress factors for biomass growth. Grain biomass growth is simulated with a grain number and grain size approach, where grain number is determined by stem weight at anthesis and a cultivar parameter (grains per stem weight). Potential grain filling rate is temperature-driven, and limited by biomass partitioned to grain.

The crop parameters derived for oats are listed in Table 1. These parameters were calibrated using a trial-and-error method with data from experiment 1. Since little data have been available for testing the APSIM-Oats model, this is the first attempt to use APSIM to simulate oats growing in semi-arid and cool regions under climate change. Table 1 lists the main parameter values in APSIM-Oats that are different from those in APSIM-Wheat.

2.6. Model calibration and validation

The model calibration was done using the data obtained in experiment 1 in two years with contrasting weather: 2009 (dry) and 2013 (wet). There were totally 40 samples including data from 2 years, 5 sowing dates and 4 replicates per year.

To derive the three cardinal temperatures for oats phenological development (thermal time in Eq. 1), a three-step procedure was used. We first calibrated T_b using a growing degree days (GDD) model with only one parameter, T_b (Monteith, 1977). We investigated a range of T_b from 0 to 10 °C, and identified the value of T_b that resulted in the best

prediction (least squares) of phenological events. We then fixed T_b at that value, and varied T_o between 10 and 30 °C to calculate thermal time by using the a two-phase linear ‘broken stick’ model with T_b and T_o and a constant development rate above T_o (i.e. no T_m) to identify T_o that resulted in the best prediction (least squares) of phenological events (Li et al., 2016). Finally, we determined T_m (setting from 30 to 40 °C) by using a triangular model (Eq. 1) while fixing T_b and T_o at the values determined in the first two steps (Supplementary Tables 1–3).

The calibrated parameters were the thermal time (°Cd) requirement for each phenological stage of the variety Caoyou 1. Subsequently, we adjusted default values of APSIM-Oats for the vernalization and photoperiod sensitivity, the potential rates of grain growth and grain filling, the number of grains per unit weight of stem and the maximum grain size using field observations. The calibrated parameters are listed in Table 1.

The validation was conducted by using observations in the experiment 1 in the three middle years (2010–2012) of the study, and all the years’ data (2009–2013) in experiment 2. Simulated and observed phenological stages, aboveground dry matter and yields were compared.

Model performance was assessed using three statistical indicators. Root mean square error (RMSE) was computed from observed (O_i) and simulated (S_i) values as

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (O_i - S_i)^2}{n}} \quad (2)$$

Normalized root mean square error (NRMSE, %), was defined as the ratio of RMSE to the observed mean:

$$NRMSE = \frac{RMSE}{O_{mean}} \times 100\% \quad (3)$$

Root Mean Square Error to Standard Deviation Ratio (RSR) provides a standardized value of the root mean square error (Moriassi et al., 2007):

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^n (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^n (O_i - O_{mean})^2}} \quad (4)$$

O_{mean} is the mean value of observed values. Values of RSR less than 0.7 are considered satisfactory while values below 0.6 indicate good to very good performance (Moriassi et al., 2007).

2.7. Simulations

APSIM-Oats was first run with historical climate data (1961–2015) to quantify impacts of historic climate change on growth duration and yield of oats. In order to separate the effects of temperature and rainfall, we ran the model for two types of climate scenarios: RUN_tem for observed temperature (1961–2015) and a fixed rainfall (1961 data) and RUN_rain for observed precipitation (1961–2015) and fixed temperature (1961 data). The year 1961 was chosen as a reference because it was the starting year of our data series and it had favorable rainfall and temperature.

APSIM-oats was then run with real historical climate data (1961–2015) and future climate scenarios (2016–2070) for five sowing dates to quantify water limited potential yield (rain-fed potential yield) (Y_r) without irrigation under no nutrient stress condition, and potential yield (Y_p), without nutrient and water stresses, using the auto-irrigation option in APSIM. In this option, soil water is brought to drained upper limit once soil water deficit reaches 10 mm. The difference between Y_r and Y_p is the yield gap due to water limitation. Sowing dates were 20 May (conventional sowing date), 10 and 20 days ahead (30 April and 10 May) and 10 or 20 days later (30 May and 9 June). Actual and potential evapotranspiration were output for each simulation year and used to calculate water stress (see next section). All the simulations

were run continuously for the studied periods without resetting initial conditions each year. This implies that water shortages are carried over from one year in the water limited scenarios.

2.8. Analysis of historical and future scenarios

2.8.1. Water stress

The coefficient for daily water stress (WS) was calculated as the relative reduction in potential evapotranspiration due to insufficient water:

$$WS = (PET - AET) / PET \quad (5)$$

where PET is potential and AET is actual evapotranspiration.

2.8.2. Potential yields and relative yield gap

The relative yield gap (RYG) due to drought was calculated as:

$$RYG = (Y_p - Y_r) / Y_p \quad (6)$$

The potential yield (Y_p) was defined as the yield simulated without water and nutrient stresses. The water limited potential yield (Y_r) is defined as the simulated rain-fed yield without nutrient stress.

2.8.3. Climate risk

Cumulative probability distributions (CPD) and box plots were used to characterize yield variability and climate risk. CPDs of water limited potential yield, potential yield, yield gap and water stress at different development stages were calculated for all sowing dates and climate scenarios.

To characterize risk, we calculated the guarantee rate (P , %), i.e. the probability of a metric not passing a critical threshold.

$$P = m/M \times 100\% \quad (7)$$

where m is the number of years that the variable is not passing the threshold and M is total number of simulated years. Higher guarantee rate P means lower risk R :

$$R = 100\% - P \quad (8)$$

For yields, “passing the threshold” means that the yield is above a certain critical minimum, while for yield gaps, “not passing the threshold” means that the gap is less than the threshold.

2.9. Statistical analysis

Linear regression was used to estimate the trends in climate variables, growth duration and yield from 1961 to 2016. The significance of the regressions was analyzed using Analysis of Variance in SPSS 20 (IBM, USA). The main effects of sowing dates on simulated actual and potential yields, relative yield gap and climate risk were analyzed using the General Linear Model procedure in SPSS 20. Least significant differences (LSD) were used to separate treatment means at the 5% level.

3. Results

3.1. Climate changes in past and future

There was a significant warming trend from 1961 to 2015 ($t_{53} = 7.01$, $P < 0.01$, t_{53} is the t -value for 53° of freedom, similarly hereinafter) but there was no significant trend in rainfall (Fig. 1a). The average daily air temperature over the whole year from 1961 to 2015 ranged from 1.0 °C to 6.2 °C in different years and increased 0.43 ± 0.06 °C per decade ($t_{53} = 7.01$, $P < 0.01$). The average annual precipitation ranged from 192 mm to 553 mm and decreased 1.9 ± 6.87 mm per decade, but this decrease was not significant ($t_{53} = -0.28$, $P = 0.78$).

There was a further warming trend in the two future climate

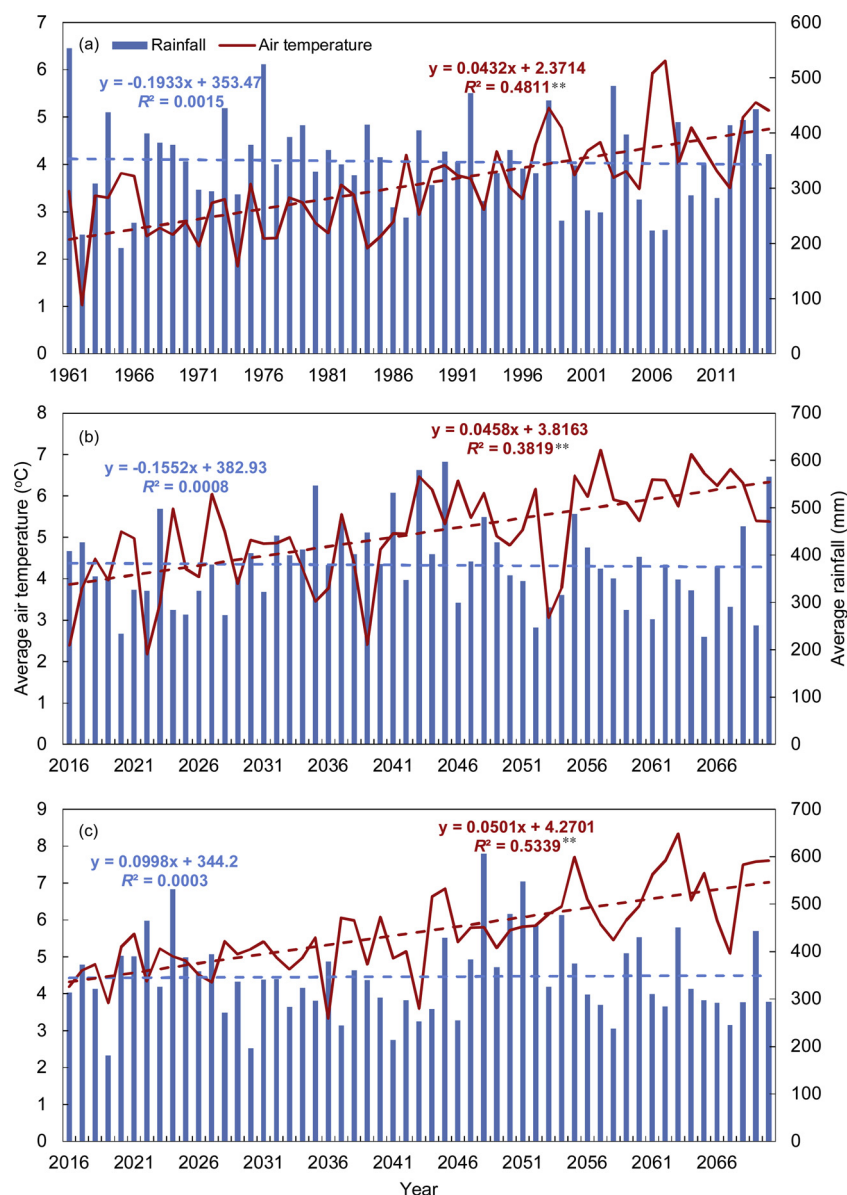


Fig. 1. Climate trends of the past (a) and two future scenarios: RCP4.5 (b) and RCP8.5 (c) for annual mean daily air temperature and annual rainfall in Wuchuan, Inner Mongolia, China. ** indicates significance at $P < 0.01$. Intercepts represent the value during the first year of the time series, i.e. at $x = 1961$ in (a) and at $x = 2016$ in (b) and (c). Slopes represent the yearly changes.

scenarios (Fig. 1 b, c) but annual precipitation would experience almost no change. The average daily air temperature would increase 0.46 ± 0.08 °C per decade ($t_{53} = 5.72$, $P < 0.01$) under RCP4.5 and 0.50 ± 0.06 °C per decade ($t_{53} = 7.79$, $P < 0.01$) under RCP8.5.

3.2. Model validation

Phenological events of emergence, flowering, and maturity simulated by APSIM-oats showed good agreement with the observations, both in calibrations and in validations (Fig. 2). The RMSE of calibration for sowing to emergence was 3.6 d, for sowing to flowering 2.0 d. and for sowing to maturity 1.9 d. The RMSE of validation for sowing to emergence was 3.0 d, for sowing to flowering 3.8 d, and for sowing to maturity 5.5 d. The NRMSE of calibration for these three phenological phases was 30.3%, 3.1% and 1.8%, respectively. The NRMSE of validation for these three phenological phases was 22.6%, 6.1% and 5.1%, respectively (Fig. 2).

For the validation, simulated and observed aboveground dry matter agreed with a NRMSE of 28.7% and RSR of 0.40 (Fig. 3a). The

simulated yields showed a good agreement with observed yields with NRMSE value of 15.3% and RSR of 0.49 (Fig. 3b). For the calibration years, the model predicted yield also obtained a good agreement with RMSE of 0.25 t ha^{-1} , NRMSE of 13.7%, and RSR of 0.54.

3.3. Limiting meteorological factors for oats growth, development and yields

The warming trend since 1961 shortened the simulated duration of vegetative growth by 1.2 ± 1.9 days per decade ($t_{53} = -0.65$, $P = 0.52$) and the reproductive period by 1.6 ± 1.5 days per decade ($t_{53} = -1.05$, $P = 0.30$), if cultivar and sowing date were held constant. The growing season was reduced by 2.8 ± 3.4 days per decade ($t_{53} = -0.84$, $P = 0.41$) (Fig. 4).

In line with the reduction in length of the growing season from 1961 to 2015, oats yield decreased by $161.8 \pm 120.4 \text{ kg ha}^{-1}$ per decade ($t_{53} = -1.34$, $P = 0.19$) (Fig. 5). The yield decrease in response to historical climate change amounted to 16.2% per decade. When using for simulations the rainfall measured in 1961 (the wettest year in the series), the increase of air temperature reduced oats yield by

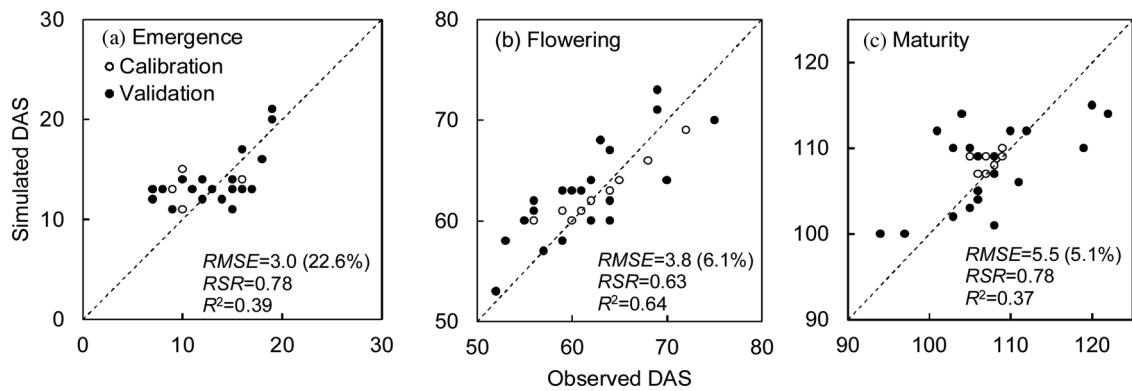


Fig. 2. Comparison of simulated and observed days from sowing (DAS) to emergence (a), flowering (b) and maturity (c) in oats for the calibration datasets (2009 and 2013) and the validation data sets (2010–2012). The results for $RMSE$, $NRMSE$ and RSR are only given for validation years.

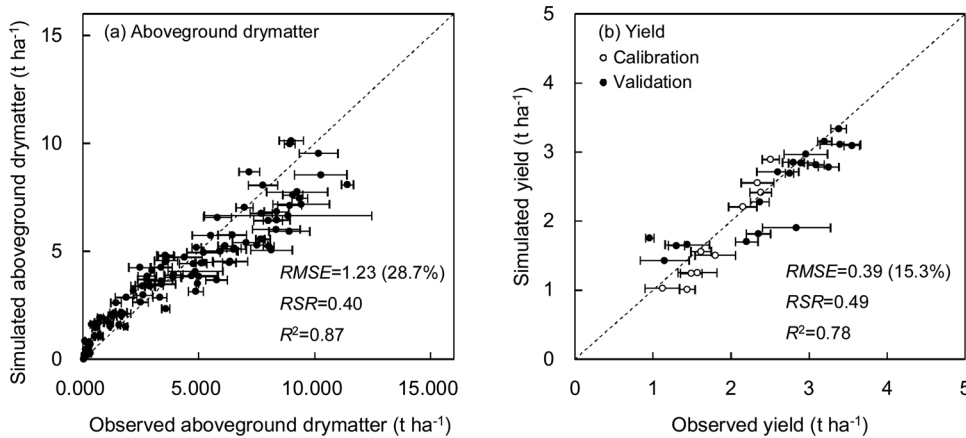


Fig. 3. Comparison of simulated and observed oats aboveground dry matter (a) and grain yield (b) against calibration (2009 and 2013) and validation datasets (2010–2012). Error bars indicate the standard errors of the mean for each sowing date in each year. The results for $RMSE$, $NRMSE$ and RSR are only given for validation years.

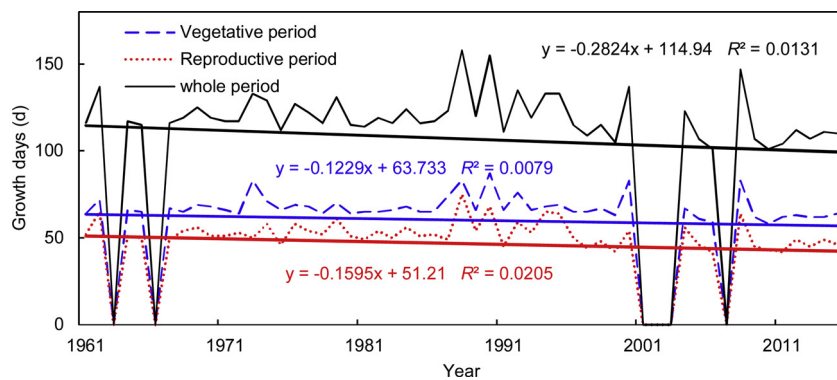


Fig. 4. Trends of simulated growth duration of oats from 1961 to 2015. Intercept values written in the figure apply to the growth days in the starting year 1961. The variable x in the regression equations is calculated as $x = \text{year} - 1961$.

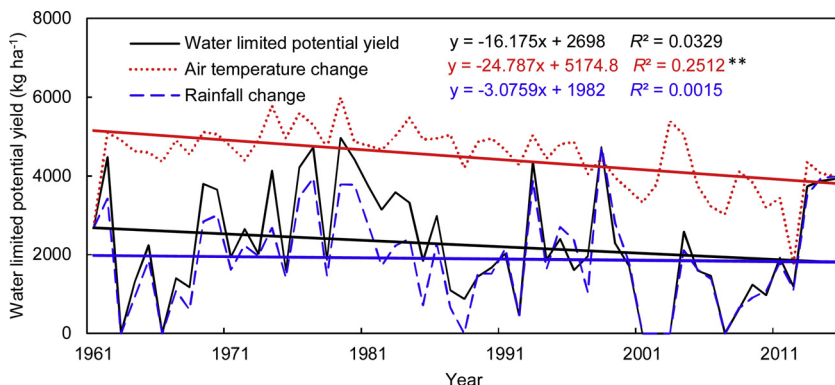


Fig. 5. Trends of simulated water limited potential yield (black line) and yields under limiting air temperature (red line) or rainfall (blue line) in 1961–2015. ** indicates the significance at $P < 0.01$. Intercept values written in the figure apply to the water limited potential yield in the starting year 1961. The variable x in the regression equations is calculated as $x = \text{year} - 1961$ (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

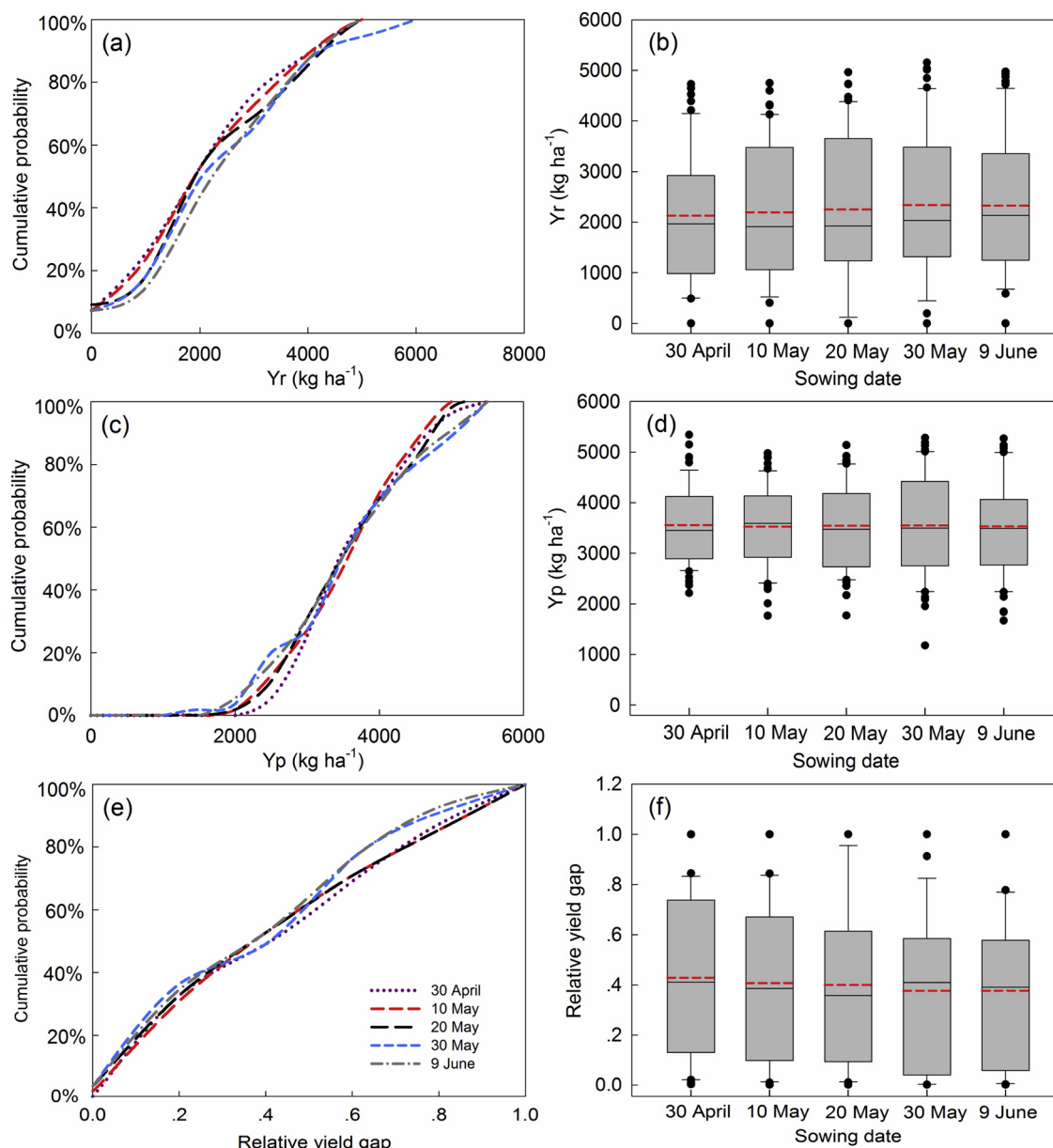


Fig. 6. Simulated water limited potential yield (Y_r) (a, b), potential yield (Y_p) (c, d) and relative yield gap (e, f) represented as cumulative probability distributions (panels on the left: a, c, e) and as boxplots (panels on the right: b, d, f) for 5 sowing dates in 1961–2015. The black lines, lower and upper edges, bars and dots in or outside the boxes in box plots represent median values, 25th and 75th, 5th and 95th, and < 5th and > 95th percentiles of all data, respectively. Means are given by red dash lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

$247.9 \pm 58.8 \text{ kg ha}^{-1}$ per decade ($t_{53} = -4.22$, $P < 0.01$). When the air temperature was kept at the level of 1961 (a slightly warmer than average year for the 60s), the oats yield decreased by $30.8 \pm 107.6 \text{ kg ha}^{-1}$ per decade ($t_{53} = -0.29$, $P = 0.78$), indicating that changes in rainfall pattern over the last 55 years are responsible for a reduction in yield, even though there was no significant change in total amount of rainfall (1961–2015). Thus, the decreasing yield trend is due to both changes in air temperature and pattern of rainfall, but the effect of rising temperature is greater than the effect of changes in rainfall pattern.

3.4. Climate risk and yield gap related to sowing dates in the past 55 years

Sowing oats 10 days later than usual (i.e. on 30 May instead of 20 May) would have increased water-limited potential yields over the last 55 years while potential yield would have been hardly affected (Fig. 6).

By sowing oats 10 days later than conventional, Y_r was 23% ($t_{54} = 2.21$, $P < 0.05$, $SE = 10.6\%$) higher than for the earliest sowing date (Table 2). As compared to the conventional sowing date of 20 May, postponing sowing by 10 days increased water-limited potential yield (Y_r) by 5.9% ($t_{54} = 1.84$, $P = 0.07$, $SE = 3.2\%$), potential yield (Y_p) by 0.3% ($t_{54} = 0.13$, $P = 0.90$, $SE = 2.5\%$), and it reduced the relative yield gap (RYG) by 10.7% ($t_{54} = -1.81$, $P = 0.08$, $SE = 5.9\%$), on average. The lack of change in Y_p in response to sowing date as compared to the much larger change in Y_r indicates that the effect of sowing date is mostly due to aligning crop growth better with the availability of rainfall. The later sowing allows kernel formation time catching the peak of the rainy season.

Sowing windows substantially affected drought risk of oats (Fig. 7). Drought risk is high during oats emergence, and the latest two sowing dates reduced this risk (Fig. 7a, b). Drought risk from emergence to oats flowering was also reduced by delaying sowing (Fig. 7c, d). More than

Table 2

Mean value and coefficient variation (CV) of water limited potential yield (Y_r), potential yield (Y_p) and relative yield gap (RYG) due to drought for 5 sowing dates in 1961–2015 and 2016–2070 under RCP4.5 and RCP8.5 scenarios.

Sowing date	Historical (1961–2015)						Future (2016–2070)											
							RCP4.5						RCP8.5					
	Average			CV			Average			CV			Average			CV		
	Y_r (kg ha ⁻¹)	Y_p (kg ha ⁻¹)	RYG	Y_r	Y_p	RYG	Y_r (kg ha ⁻¹)	Y_p (kg ha ⁻¹)	RYG	Y_r	Y_p	RYG	Y_r (kg ha ⁻¹)	Y_p (kg ha ⁻¹)	RYG	Y_r	Y_p	RYG
30 April	2131 a	3559 a	0.43 a	64%	21%	73%	1858 a	2814 a	0.37 a	60%	18%	92%	1368 a	2719 a	0.53 a	87%	24%	70%
10 May	2195 a	3527 a	0.41 a	62%	23%	77%	1807 a	2678 a	0.35 a	59%	19%	99%	1322 a	2512 ab	0.51 a	87%	23%	75%
20 May	2249 a	3546 a	0.40 a	63%	24%	79%	1879 a	2620 a	0.30 a	55%	21%	110%	1324 a	2335 b	0.46 a	81%	24%	85%
30 May	2338 a	3548 a	0.38 a	62%	28%	83%	2041 a	2682 a	0.27 a	53%	26%	121%	1396 a	2353 b	0.45 a	77%	22%	89%
9 June	2328 a	3530 a	0.38 a	59%	27%	80%	2008 a	2678 a	0.28 a	55%	26%	119%	1391 a	2380 b	0.46 a	78%	24%	84%
SE	84.2	52.5	0.02	–	–	–	65.1	36.2	0.02	–	–	–	67.1	35.1	0.02	–	–	–
P	0.928	1.000	0.898	–	–	–	0.752	0.534	0.405	–	–	–	0.994	0.003	0.777	–	–	–

Same small letter indicates no significant difference between sowing dates at $\alpha = 0.05$.

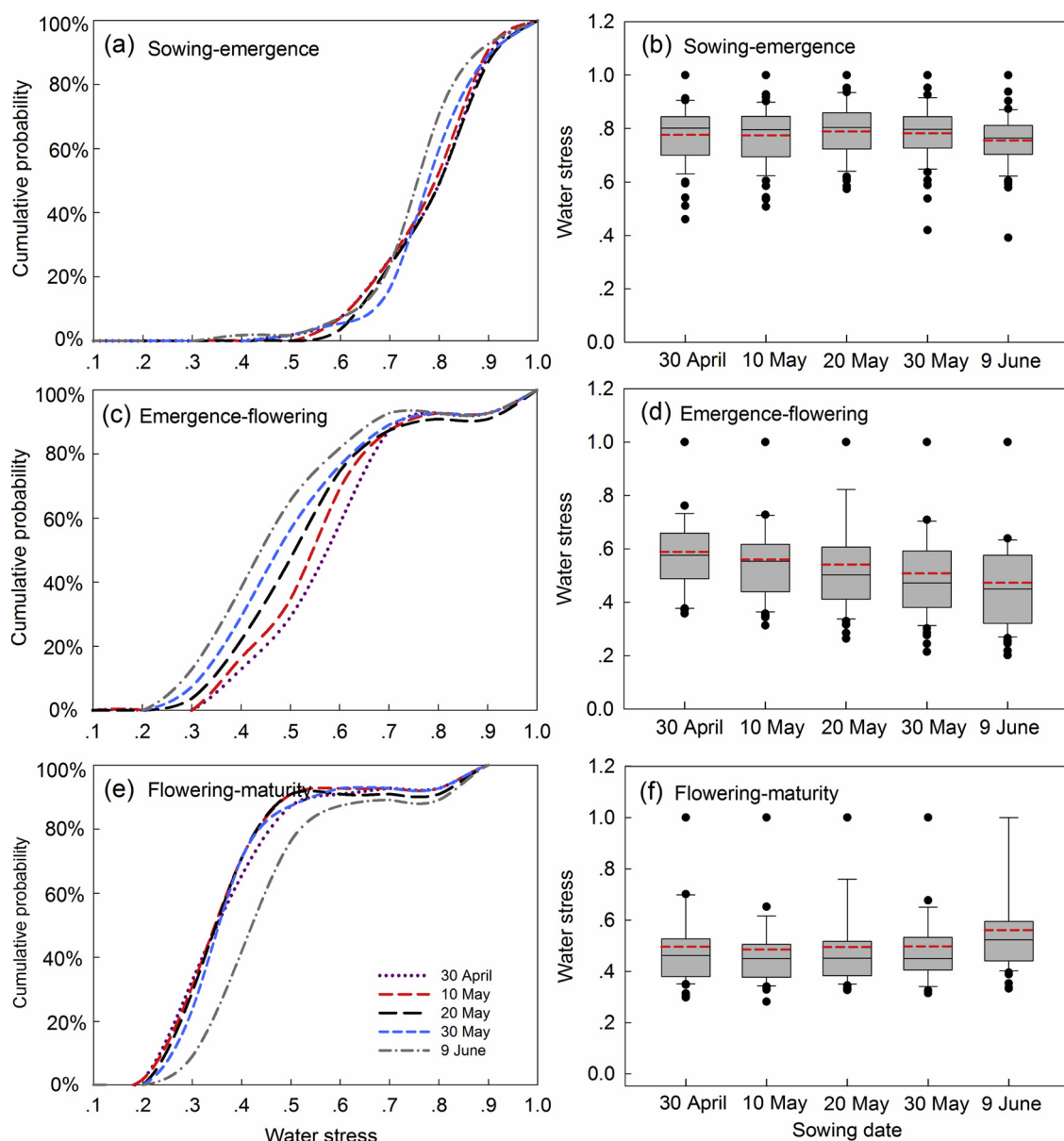


Fig. 7. Water stress represented as cumulative probability distribution (left panels: a, c, e) and as boxplots (right panels: b, d, f) in the duration of phenological stages of oats: sowing to emergence (a, b), emergence to flowering (c, d) and flowering to maturity (e, f) stages. Results were generated with simulation for 5 sowing dates and historical weather in 1961–2015. For definitions in box plots, see the legend of Fig. 6.

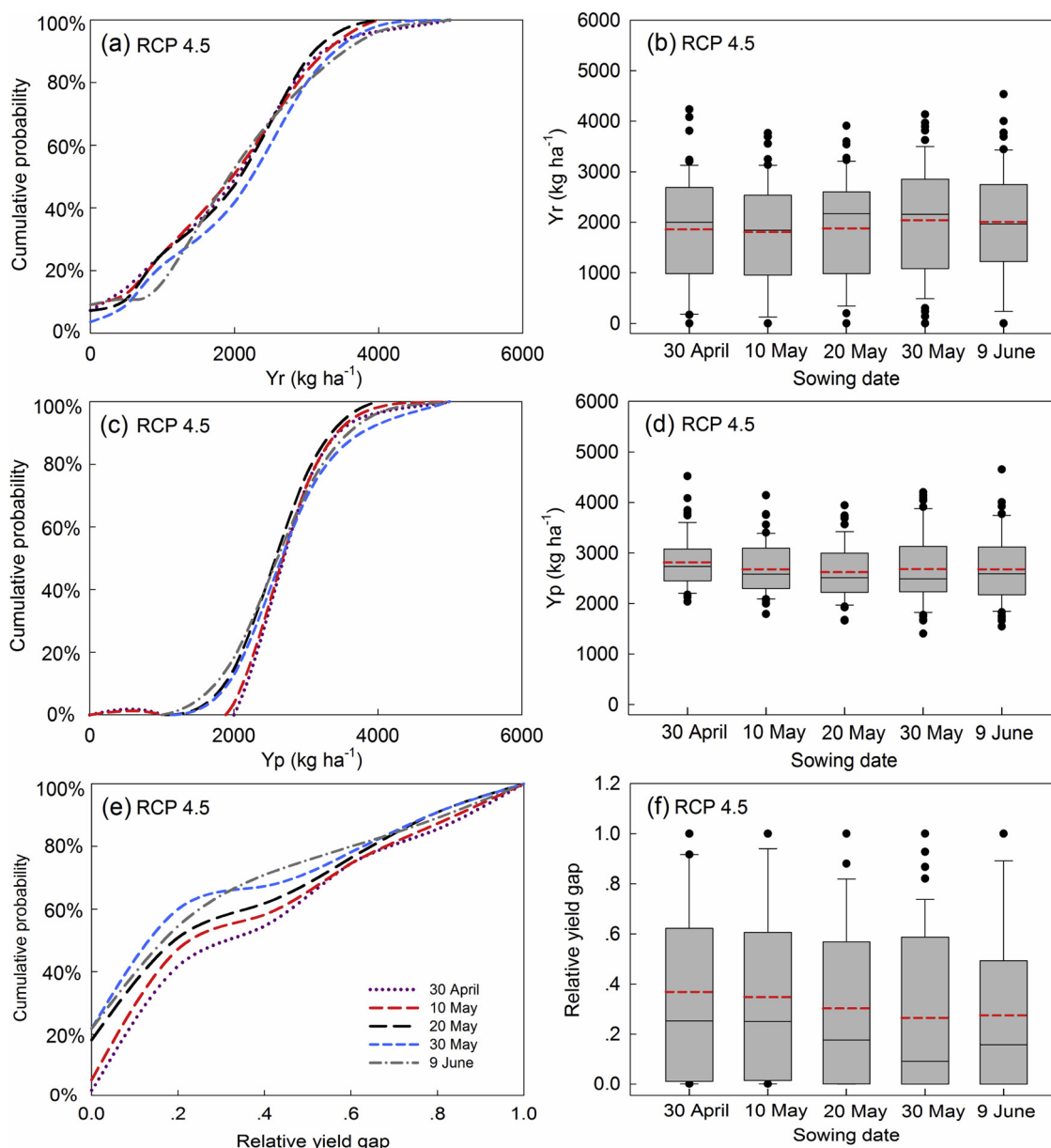


Fig. 8. Simulated water limited potential yield (Y_r) (a, b), potential yield (Y_p) (c, d) and relative yield gap (e, f) represented as cumulative probability distributions (panels on the left: a, c, e) and as boxplots (panels on the right: b, d, f) for 5 sowing dates in 2016–2070 under the scenarios RCP4.5. For definitions in box plots, see the legend of Fig. 6.

half (53%) of the rainfall (on average from 1961 to 2010) was concentrated in July to August. Therefore, the latest sowing date greatly increased the risk of water stress during the reproductive period (flowering to maturity) (Fig. 7e, f).

3.5. Climate risk and yield gap response to sowing dates in future scenarios

Sowing oats 10 days later than conventional would also enhance yields and mitigate climate risk under the two RCP scenarios (Table 2, Fig. 8). Sowing oats on 30 May would increase Y_r by 9.4% ($t_{54} = 2.77$, $P < 0.01$, $SE = 3.4\%$) on average compared to conventional sowing date under two RCPs (Table 2). While the water-limited potential yields were increased, potential yields of oats under both the RCP4.5 and RCP8.5 scenarios were decreased by later sowing due to a shorter growth period (Figs. 8 and 9). Thus, later sowing (end of May) would decrease the yield gap in the future. Delayed sowing date also reduced water stress during both vegetative and reproductive growth periods

(Fig. 10 and 11).

The climate risk was higher under RCP8.5 than under RCP4.5. The water limited potential yields are significantly lower under RCP8.5 than under RCP4.5 as a result of lower rainfall in RCP8.5 (Fig. 12).

4. Discussion

The warming trend under climate change shortened the developmental duration of oats through increasing development rate, and the changes in temperature and rainfall pattern reduced crop growth rate. Both changes contribute to a reduction in yield. Changes in rainfall patterns over time had negative consequences for simulated yields in both past and future climates, but this effect was smaller than the effect of warming. Optimizing sowing time could reduce the climate risks. The simulations indicated that sowing oats 10 days later than usual would have increased yield in the period 1961–2015 and may do so in the future due to a reduction in water stress, especially during vegetative

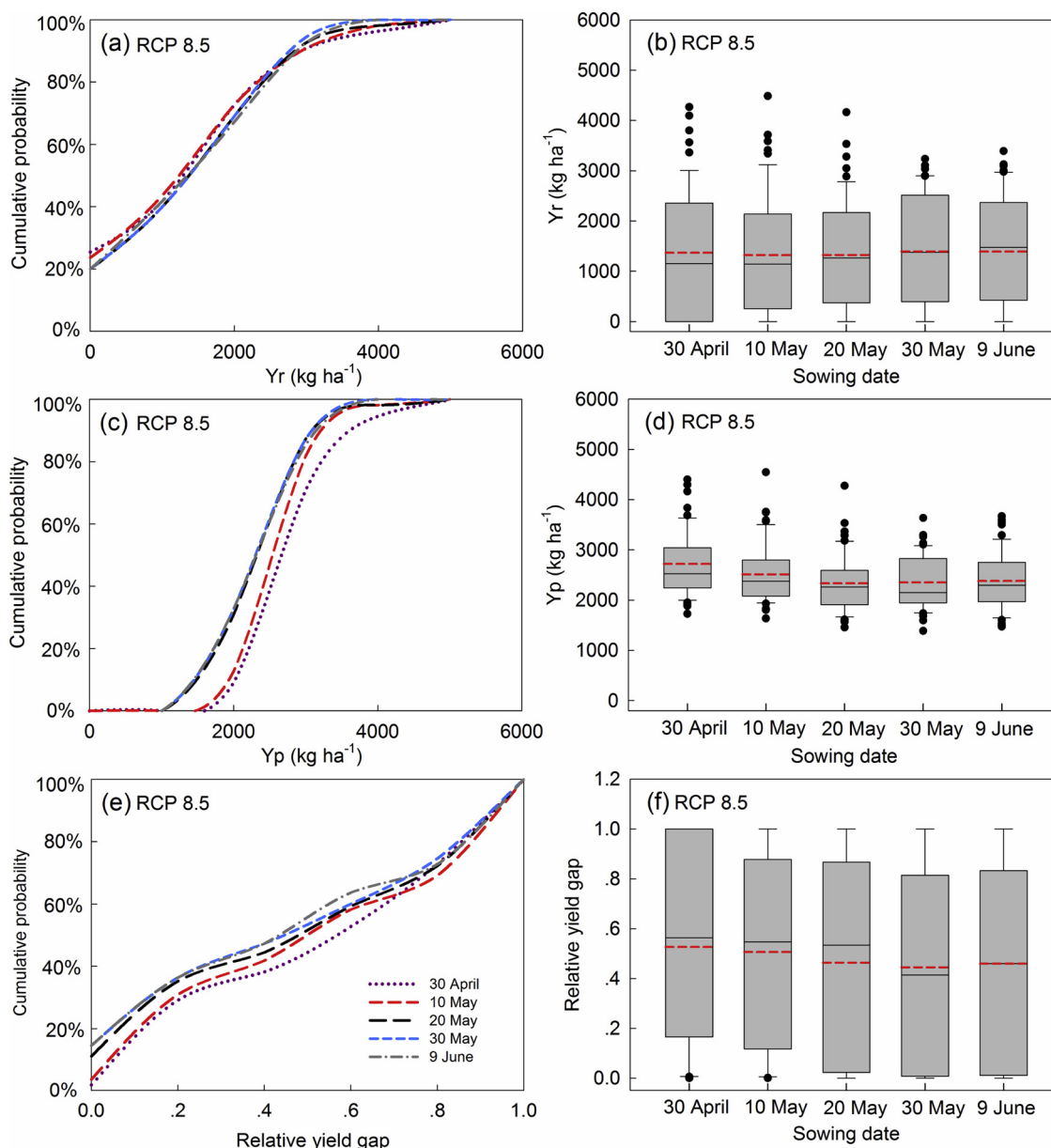


Fig. 9. Simulated water limited potential yield (Y_r) (a, b), potential yield (Y_p) (c, d) and relative yield gap (e, f) represented as cumulative probability distributions (panels on the left: a, c, e) and as boxplots (panels on the right: b, d, f) for 5 sowing dates in 2016–2070 under the scenarios RCP8.5. For definitions in box plots, see the legend of Fig. 6.

growth phase. By delaying sowing 10 days, the risk of yields falling below a threshold of 3000 kg ha^{-1} was reduced by 2.7% under future climate scenarios, compared with conventional sowing time. Sowing more than 10 days later than the usual would expose the crop to high summer temperature during its early growth and accelerate its development. This would not have been an option in the past because drought risk would have been too high from flowering to maturity and the growth period would have been shortened due to the accelerated development. The validation of APSIM-Oats showed that the model could successfully simulate the growth, development and yield of oats in a cool and dry continental climate.

4.1. Model performance

An APSIM-Canola study showed that using data from contrasting environmental conditions (at least two seasons) is an effective calibration method, particularly with in-season growth measurements (He

et al., 2017). In our study, we used two years with a large difference in rainfall to do the calibration. Rainfall was 287 mm in 2009 and 423 mm in 2013. Then, the model was validated by using 3 additional years of data, based on crop growth measurements for 5 sowing dates. This procedure allowed satisfactory model performance in the validation for yield with a normalized root mean square error (NRMSE; Eq. 3) of 15.3% and a ratio of the root mean square error to the standard deviation of the data with respect to the simulated mean (RSR; Eq. 4) of 0.49 (less than 0.6). Observed biomass was slightly overestimated by APSIM-Oats in early growth stages and somewhat underestimated in later stages. The larger simulation errors (RMSE) in biomass as compared yield was mainly due to the smaller sampling area for dry matter during crop growing season (1 m^2) as compared to the sampling area for final yield (4 m^2). These mismatches could be also due to effects of water stresses on phenological development that were not considered in the model (Boote et al., 2013). Further model development might consider the effect of drought on oats development (Li et al., 2016). A

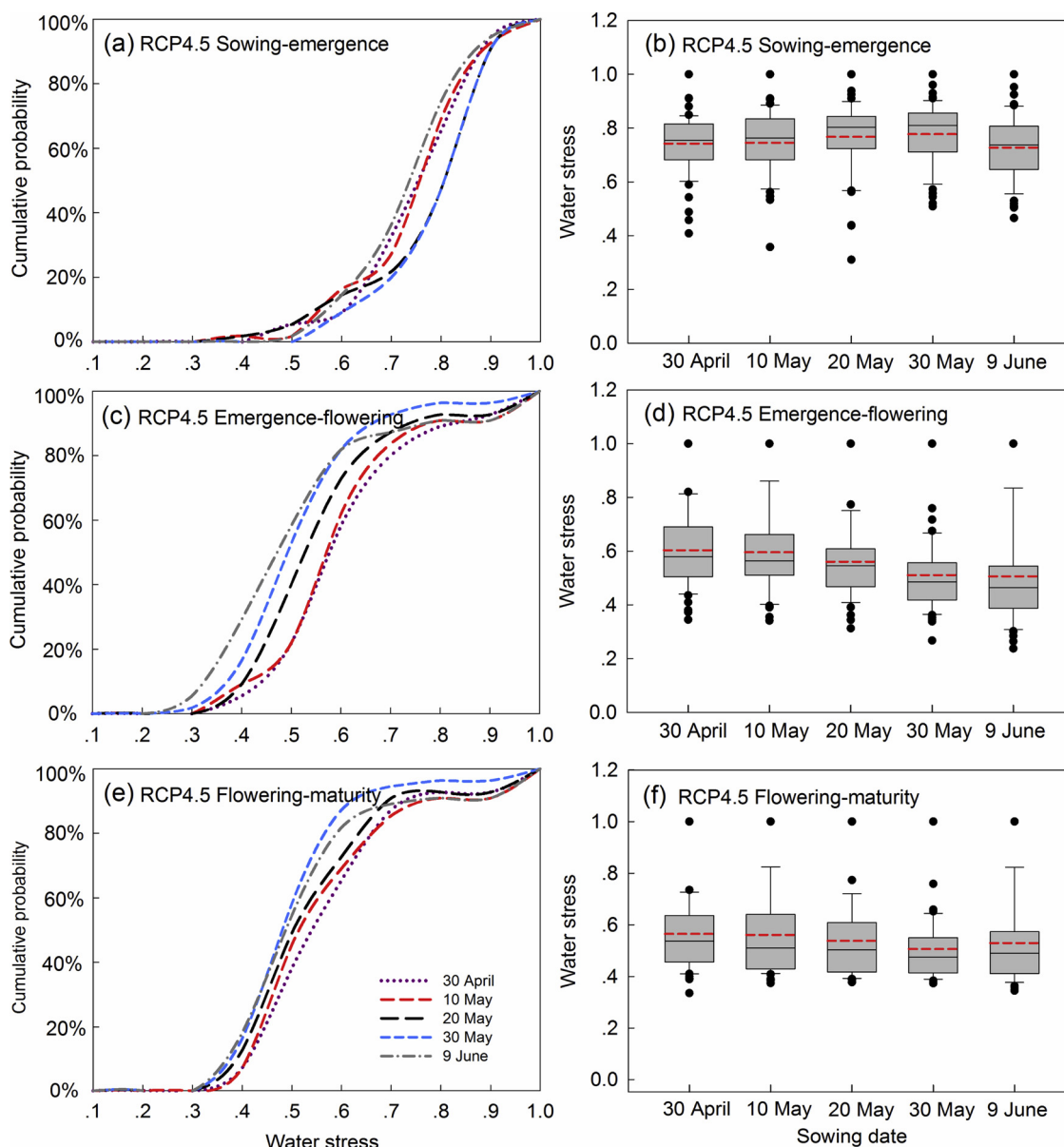


Fig. 10. Water stress represented as cumulative probability distribution (left panels: a, c, e) and as boxplots (right panels: b, d, f) in the duration of phenological stages of oats: sowing to emergence (a, b), emergence to flowering (c, d) and flowering to maturity (e, f) stages. Results were generated with simulation for 5 sowing dates and historical weather in 2016–2070 under the scenarios RCP4.5. For definitions in box plots, see the legend of Fig. 6.

higher base temperature of oats has been found for the grain filling phase than for the pre-flowering phase (Olesen et al., 2012). In our study, the accuracy of phenological event simulation was minimized by using the same base temperature for all development stages.

4.2. Yield-limiting meteorological factors in oats

Impacts of climate change on yield depend on location, soil and other environmental factors. Temperature is the main variable that regulates the rate of crop development (Nasim et al., 2016). Higher temperatures have a positive effect on grain yield in the cooler and wetter southern part of Western Australia because a faster crop development caused by warmer temperatures moves the grain filling period into a wetter part of the season (van Ittersum et al., 2003). However in most cases, an increase of temperature accelerates crop development, reducing accumulation of assimilates and grain filling (Liu et al., 2013), which was also the case in our study. In our study, climate warming induced a faster crop development which then caused a mismatch with

the rainfall pattern when the sowing time or cultivar was not adapted to the changed conditions. As a result of climate change, there were water shortages during vegetative growth, but these can largely be overcome by later sowing.

4.3. Potential yield and yield gap due to rainfall under climate change

The warming trend had a negative effect on potential yield. Our result aligns well with previous research about maize in China (Chen et al., 2013). The negative effect of the warming trend on potential yield is probably due to the shortened crop growth period allowing less time for acquisition of resources and accumulation of biomass (Chen et al., 2013). Furthermore, increasing temperature during the reproductive stage hastens crop senescence and decreases kernel weight and grain yield potential (Asseng et al., 2011). The negative impact of increasing air temperature could be offset by adjusting sowing time. Sowing oats later than currently would significantly increase water-limited potential yields as compared to earlier sowing and reduce the

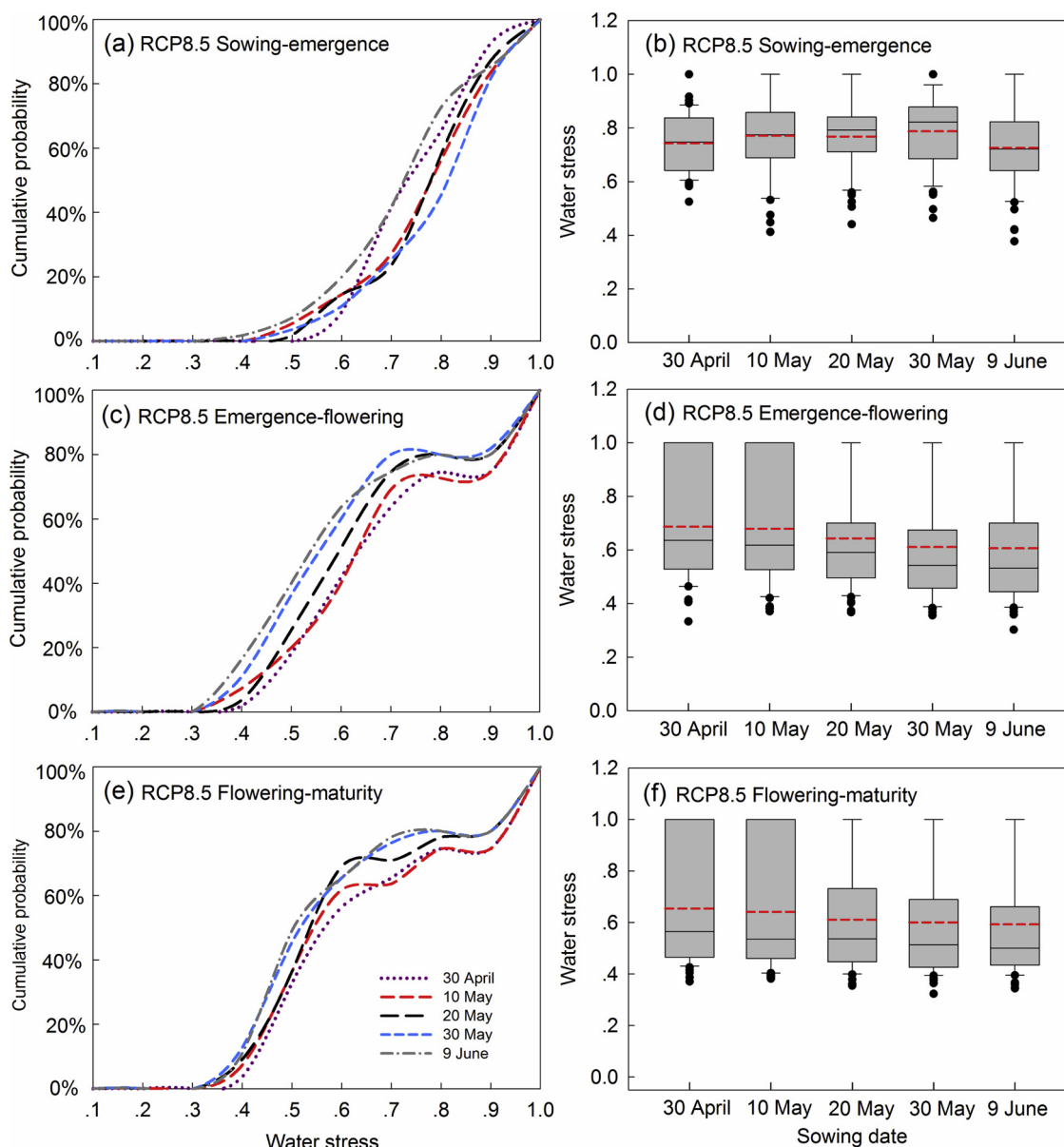


Fig. 11. Water stress represented as cumulative probability distribution (left panels: a, c, e) and as boxplots (right panels: b, d, f) in the duration of phenological stages of oats: sowing to emergence (a, b), emergence to flowering (c, d) and flowering to maturity (e, f) stages. Results were generated with simulation for 5 sowing dates and historical weather in 2016–2070 under the scenarios RCP8.5. For definitions in box plots, see the legend of Fig. 6.

yield gap.

In both historical and future simulations, there was a chance of no oats yield for all the sowing dates. The causes for this included: dry soil at sowing time (crop cannot germinate) or little rain during certain stages (crop dies due to drought). The problems of dry soil at sowing could be solved by supplying small amount of water at sowing to ensure emergence (Mo et al., 2017). Y_r can be the same as Y_p in some years when the rainfall is sufficient for oats growth.

4.4. Managing climate risks

The simulations indicate that delaying oats sowing 10 days compared to farmers' practice would reduce climate risk by improving the alignment of crop requirement with rainfall patterns and temperature. In the North China Plain, delaying winter wheat sowing led to a 4 to 6% increase in grain yield (Wang et al., 2012). Earlier sowing increased yield due to better heat use in Northeast China (Liu et al., 2013), however, in our case, sowing later obtained a better harmony of rainfall

and temperature for oats. In Pakistan, a 7 to 14 days delay in sowing of sunflower reduced crop yield significantly due to shortening crop growth duration and a quick shift from vegetative growth to reproductive period when the temperature is high (Nasim et al., 2016). Crop productivity in Inner Mongolia is mainly limited by insufficient precipitation and annual and within-season variation in rainfall. Late sowing will allow the most drought sensitive phase in oats to be better aligned with the time of largest water availability, resulting in increased yield and reduced climate risk when the premise of crop maturity was achieved.

Delayed sowing was found to be an effective strategy to reduce future climate risk for oats in the study region under both climate change scenarios RCPs 4.5 and 8.5, improving water availability during crop growth. While early sowing of oats would increase potential yield, the water-limited potential yield would decrease with earlier sowing due to an increase of drought risk. On the other hand, late sowing could significantly increase water limited potential yield under rain-fed conditions and reduce the yield gap.

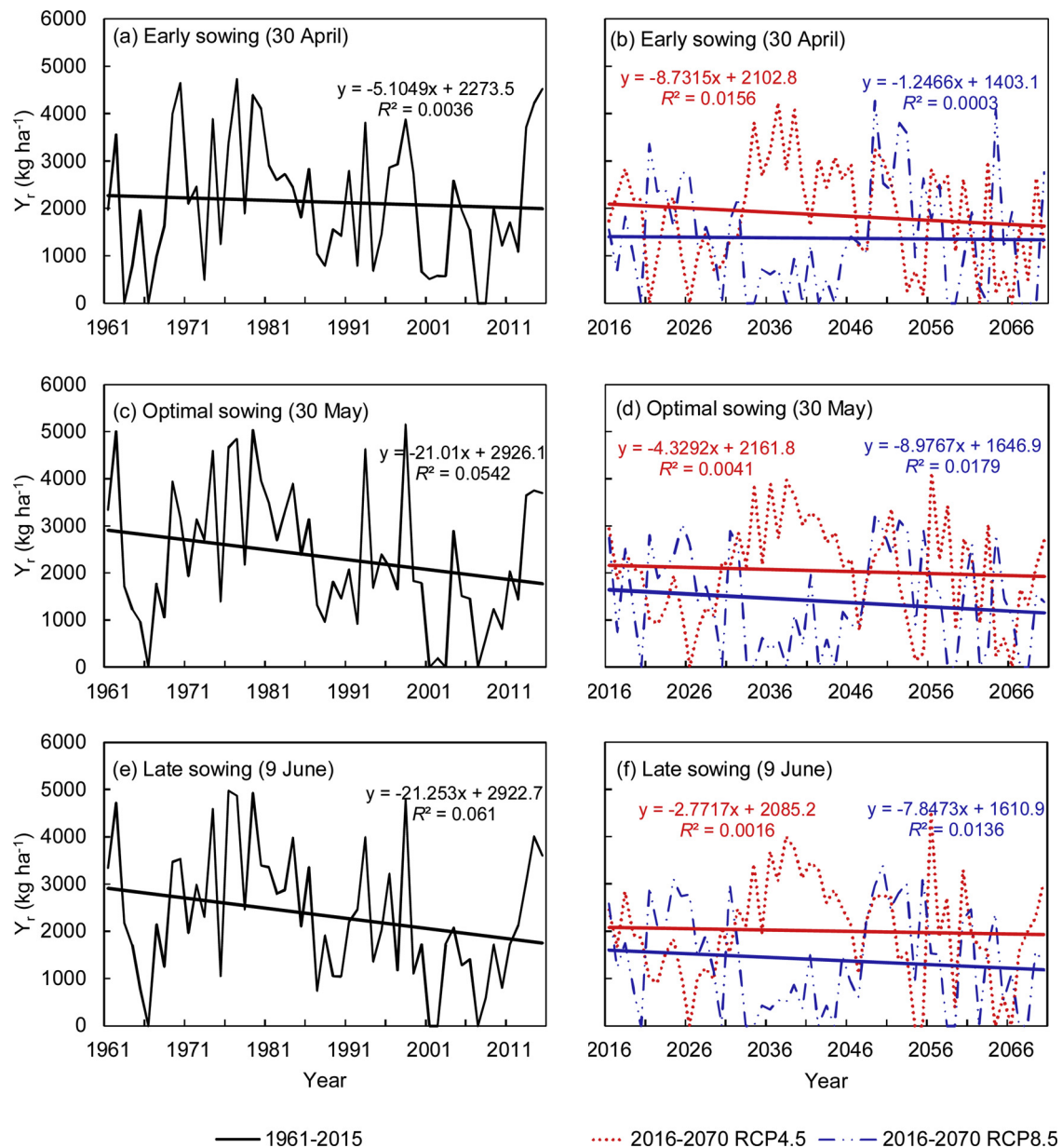


Fig. 12. Simulated water limited potential yields (Y_r) when sowing oats on 30 April (a, b), 30 May (c, d) and 9 June (e, f) in 1961–2015 (a, c, e) and 2016–2070 under RCP4.5 and RCP8.5 (b, d, f). The solid lines were regression trend line. Intercept values written in the figure apply to the water limited potential yields (Y_r) in the starting year 1961 (left panels: a, c, e) and 2016 (right panels: b, d, f). The variable x is calculated as $x = \text{year} - 1961$ (a, c, e) and $x = \text{year} - 2016$ (b, d, f).

Using better adapted genotypes that are late-maturing and drought-resistant, might also increase potential yield as it would allow a longer growing season offsetting the stimulatory effect of warming on developmental rate and deal with drought and other weather extremes better (Yin et al., 2016). New cultivars with higher thermal requirements and later maturity could be introduced to expand oats growth duration and compensate yield loss due to the acceleration in crop development caused by increased temperatures (Tao et al., 2013; Huang et al., 2018; Liu et al., 2018). This cultivar shift happens in rice and wheat under climate change (Xiao and Tao, 2016; Bai et al., 2016a, b; Liu et al., 2012). Oats often grows as a short-season crop in cool regions where the temperature sum is not enough for wheat to complete its growth cycle, therefore, some oats in semi-arid cool regions like the studied region might be replaced by spring wheat when the increasing temperature under climate change allows that. As the weather data series shows a time trend, gradually shifting sowing dates might be considered as an adaptation strategy (Parker et al., 2016). Agronomic

technique innovation for soil water conservation and protection against soil erosion would also be useful strategies, e.g. plastic and residue mulching, zero tillage, deep loosening tillage (Song et al., 2013) to mitigate the negative impacts of drought, and furrow-ridge tillage or film cover to reduce drought risk and increase soil temperature (Dong et al., 2017). Changes in the cropping systems, e.g. rotations and intercropping (Bai et al., 2016a, b), could be useful to increase resource use efficiency and yield stability under conditions of variable rainfall and poor soil fertility. Intercropping oats with legume or crops using less water might be a good choice to adapting climate change in the future.

5. Conclusion

APSIM-Oats provided a robust prediction of the growth and yield of oats in semi-arid Inner Mongolia. The historical climate change trend 1961–2015 resulted in a simulated yield decrease of 161.2 kg ha⁻¹ per

decade, mostly due to a significant temperature increase of 0.43 °C per decade. While the annual amount of precipitation did not change significantly over the period 1961–2015, a deteriorated alignment of rainfall pattern with crop demand for unchanged sowing time contributed 30.8 kg ha⁻¹ per decade to the yield decrease. Delayed sowing is a practical strategy to reduce climate risk and enhance yield as it better aligns crop water and temperature demand with the availability of these resources. Applying longer season cultivars, film cover to improve water availability and changing sole oats cultivation to intercropping are additional adaptation strategies that may increase future oats yields and resilience of cropping systems in this region. Our results provide useful predictions for improving crop yield and risk management in an environmentally fragile and sensitive region undergoing climate change.

Acknowledgements

The research was supported by National Key R&D Program of China (2017YFC1502404), IWH Research & Development Support Program (JZ0145B752017, 582017), National Key Research and Development Program of China (2016YFD0300202), the International Cooperation and Exchange of the National Science Foundation of China (31461143025).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.agrformet.2018.12.019>.

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